

QUANTUM COMPUTATIONS

PACS numbers: 42.79.Vb; 03.67.Lx; 42.50.Ex
DOI: 10.1070/QE2015v045n10ABEH015740

Nanophotonic quantum computer based on atomic quantum transistor

S.N. Andrianov, S.A. Moiseev

Abstract. **We propose a scheme of a quantum computer based on nanophotonic elements: two buses in the form of nanowaveguide resonators, two nanosized units of multiatom multiqubit quantum memory and a set of nanoprocessors in the form of photonic quantum transistors, each containing a pair of nanowaveguide ring resonators coupled via a quantum dot. The operation modes of nanoprocessor photonic quantum transistors are theoretically studied and the execution of main logical operations by means of them is demonstrated. We also discuss the prospects of the proposed nanophotonic quantum computer for operating in high-speed optical fibre networks.**

Keywords: *quantum computer, quantum memory, nanowaveguide ring resonator, quantum dot, quantum logical gates.*

1. Introduction

During the last decades the choice and development of a physical scheme for a universal quantum computer and small quantum calculators remain an urgent problem of theoretical and experimental studies. At present, more and more attention is paid to the construction of a hybrid scheme of a quantum computer, which can comprise a few quantum processors and a multiqubit quantum memory, having different physical carriers. In particular, such a scheme is intensely elaborated for a computer with superconducting qubits [1–4]. In spite of impressive results, it is still difficult to achieve significant suppression of decoherence effects in such qubits [5], which hampers further progress in the development of this computer. The arising difficulties stimulate the search for new multiparticle qubits with long decoherence time (see, e.g., [6, 7] and references therein), as well as for faster techniques of implementing quantum calculations. In the latter case, we consider as promising the photonic systems, known to accelerate substantially the execution of the data processing due to the noninertial nature of photons [8]. Moreover, photonic qubits find direct application in quantum communication lines and, therefore, do not need additional conversion, when the photonic quantum computer is incorporated in a quantum network.

The main version of a photonic quantum computer is a linear quantum computer [9–11]. However, the operation of its quantum gates is probabilistic, so that its stable functioning requires too many physical qubits [12]. These difficulties are due to the impossibility of using photons directly to execute two-qubit operations, such as controlled-NOT (CNOT), or controlled phase rotation, since the interaction of photons is extremely weak under usual conditions. Considerable efforts to solve this problem during the last decade were aimed at finding methods for essential enhancement of photon–photon interactions in different resonance atomic systems, e.g., using the effect of mutual phase modulation of weak light fields in a scheme of double electromagnetically induced transparency [13–15]. In spite of significant progress of these studies, including the appearance of new promising schemes of implementing this approach, a necessary enhancement of photon–photon interaction is still not achieved experimentally. To overcome the existing difficulties the authors of Ref. [16] proposed to use the optical waveguides, tunnel-coupled with the photonic logical qubits in coupled photonic resonators, where the double-qubit operations are executed by means of the transfer of single-photon excitation from the waveguides into a quantum dot, connected to them end-to-end. However, this scheme remains not very efficient.

In the present paper, we develop an alternative way of implementing CNOT operation, based on the quantum control of the excitation transfer between two closely spaced microresonators via the quantum states of the atom (quantum dot), operating in the mode of a control 'grid' of a photonic quantum transistor. Note that recently the control of the single-photon state transfer between optical waveguides has been successfully implemented experimentally using a whispering-gallery resonator with a single rubidium atom [17]. An all-optical routing of single photons has been also experimentally demonstrated [18]. Using the technical possibilities of a waveguide optical resonator, or whispering-gallery resonator, containing only a single controlling atom, one can place the second resonator closely to this atom and choose the orientation of this resonator and the suitable distance by means of existing nanopositioners. Thus, one can implement the necessary coupling of two nanowaveguide ring resonators via a single quantum dot.

Below we describe the basic properties of the considered nano-optical scheme of the computer and the execution of basic quantum operations by this scheme. The proposed method allows, in principle, the execution of logical opera-

S.N. Andrianov Institute of Advanced Research, Academy of Sciences of the Republic of Tatarstan, ul. Levo-Bulachnaya 36a, 420111 Kazan, Russia; Kazan Quantum Centre of Kazan National Research University, ul. K. Marksa 10, 420111 Kazan, Russia; e-mail: andrianovsn@mail.ru;
S.A. Moiseev Kazan Quantum Centre of Kazan National Research University, ul. K. Marksa 10, 420111 Kazan, Russia; Kazan E.K. Zavoisky Physical-Technical Institute (KPhTI) of the Kazan Scientific Centre, Russian Academy of Sciences, ul. Sibirskii trakt 10/7, 420029 Kazan, Russia; e-mail: samoi@yandex.ru

Received 25 December 2014; revision received 25 July 2015
Kvantovaya Elektronika **45** (10) 937–941 (2015)
Translated by V.L. Derbov

tions with the reduced number of steps and high enough efficiency. First, we describe the elementary operations with single-photon fields that in the subsequent part of the paper are used to implement single- and double-qubit gates.

2. Operation of excitation transfer

We use photonic logical qubits each encoded as a single-photon excitation, distributed over a pair of nanowaveguide ring resonators coupled via a quantum dot. All pairs of resonators with quantum dots are located along two Bragg nanowaveguide resonators (nanowaveguide buses), via which the qubits are transferred to the resonators from the two-section quantum QMa and QMb memory cells (Fig. 1). Consider the main logical operations with a single logical qubit. First, we transfer the state of arbitrarily chosen logical qubit from the quantum QMa and QMb memory cells to one pair of free ring resonators, e.g., the pair 1a and 1b. The controlling atom 1c is in the state $|b\rangle_c$, in which the interaction between the light fields of two adjacent resonators remains supressed.

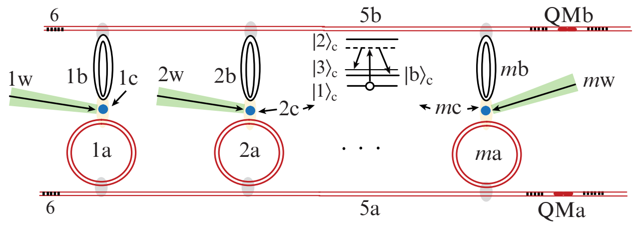

Figure 1. Architecture of a nanophotonic quantum computer with multiqubit memory:
1a and 1b, 2a and 2b,..., *m*a and *m*b are mutually orthogonal nanowaveguide ring resonators of the first, second,..., *m*th logical qubits; 1c, 2c, ..., *m*c are quantum dots; 5a, 5b are nanowaveguides; 1w, 2w, ... , *m*w are tapered optical waveguides; 6 are Bragg gratings; QMa and QMb are cells of quantum memory for logical qubits. The inset illustrates the quantum states of the three-level gate atom.

The transfer of photonic qubits from the cell of quantum memory starts after the reconstruction of the macroscopic coherence, recorded in memory atoms with different frequency mismatch [19]. The M out-of-phase atomic coherences, each corresponding to a separate qubit, correspond to M photonic qubits. The phasing of each atomic coherence will be accompanied by the emission of a photon and its transfer into nanowaveguide buses 5a and 5b. Then the single-photon excitation is transferred into the pair of resonators (1f and 1b) tuned to the resonance with the nanowaveguide buses.

The efficient transfer of the photonic qubit from the memory into both resonators occurs at a definite moment of time t_s after the beginning of the interaction. This is possible under the optimal choice of the parameters of atomic ensembles located in the memory cells, for the corresponding constants of coupling between the resonators and nanophotonic waveguides [20, 21]. Immediately after the transfer of the photonic qubit at $t = t_s$, the connection of resonators 1a and 1b with the nanowaveguide buses is interrupted. For example, one can implement such interruption by changing the effective coupling length between the resonator and nanowaveguide bus by means of an external laser pulse irradiating the place of the contact [22].

Note that although the frequencies of two adjacent ring resonators coincide with each other, the direct interaction and exchange of single-photon excitations between them remain suppressed due to the choice of different spatial orientation of the resonators and the transfer of the controlling atom into the blocking quantum state $|b\rangle_c$ (Fig. 1). After the transfer of the photonic logical qubit into two resonators (1a and 1b) and switching off the connection between these resonators and the nanowaveguide buses, we transfer the controlling atom from the blocking state $|b\rangle_c$ into the working state $|1\rangle_c$. For this purpose we use nonresonance double-frequency laser radiation tuned to the resonance with the transition $|b\rangle_c \rightarrow |1\rangle_c$ and transmitted through a special tapered optical waveguide 1w (Fig. 1).

If the frequency of the atomic transition between states $|1\rangle_c$ and $|2\rangle_c$ is close enough to the frequency of resonators 1a and 1b, then the light fields in the two resonators begin to interact with each other by transferring excitations via state $|2\rangle_c$ of the controlling atom. Below we describe the dynamics of this interaction in detail.

The Hamiltonian of the considered system has the form

$$H = H_0 + H_1, \tag{1}$$

where

$$H_0 = H_a + H_r, \tag{2}$$

is the base Hamiltonian;

$$H_1 = H^{(1)}_{r-a} + H^{(2)}_{r-a} \tag{3}$$

is the perturbation Hamiltonian;

$$H_a = \varepsilon_\mu S^{(0)}_{\mu\mu} \tag{4}$$

is the Hamiltonian of a gate atom in terms of operator generators $S^{(0)}_{\mu\mu}$ of the SU(3) group; ε_μ is the energy of level μ;

$$H_r = \hbar\omega_r a_1^+ a_1 + \hbar\omega_r a_2^+ a_2 \tag{5}$$

is the Hamiltonian of the photons in nanowaveguide ring resonators 1 and 2; ω_r is the frequency of photons;

$$H^{(l)}_{r-a} = G^{(l)}_{21} S^{(0)}_{21} a_l + G^{(l)*}_{21} S^{(0)}_{12} a_l^+ \tag{6}$$

is the Hamiltonian of interaction between the photons in the resonator and the three-level gate atom at the $1 \rightarrow 2$ transition within the framework of Janes–Cummings model; $G^{(l)}_{21}$ is the coupling constant; $S^{(0)}_{21}$ and $S^{(0)}_{12}$ are the transition operators; a_l and a_l^+ are the operators of creation and annihilation of photons in the resonators; and $l = 1, 2$.

Consider a particular case, when the frequencies of the photons in ring resonators 1a and 1b are detuned from the frequency of the $|1\rangle_c \leftrightarrow |2\rangle_c$ transition of the gate atom by the value of Δ, exceeding the constant of the coupling of the atoms with the modes of the ring resonators. The controlled frequency mismatch can be implemented by using an external laser pulse [23], quickly changing the effective optical length of the resonator and causing the adiabatic change in the resonator operating frequency within a wide spectral range. To describe the quantum dynamics of the photonic qubit for the sufficiently large frequency mismatch Δ, we can use the Schrieffer–Wolff transformation, which to the first-order terms yields the expression for the effective Hamiltonian

$$H_s = H_0 + \frac{1}{2}[H_1, s] \tag{7}$$

provided that

$$H_1 + [H_0, s] = 0. \quad (8)$$

Choosing appropriately the parameter s, we arrive at the expression for the effective Hamiltonian

$$H_s = \varepsilon_\mu S_{\mu\mu}^{(0)} + \hbar\omega_r a_1^+ a_1 + \hbar\omega_r a_2^+ a_2 + \frac{1}{\hbar\Delta}\left(|G_{21}^{(1)}|^2 + |G_{21}^{(2)}|^2\right)$$

$$\times S_{21}^{(0)} S_{12}^{(0)} + \frac{1}{\hbar\Delta}\left(|G_{21}^{(1)}|^2 a_1^+ a_1 + |G_{21}^{(2)}|^2 a_2^+ a_1\right)(S_{22}^{(0)} - S_{11}^{(0)})$$

$$+ \frac{1}{\hbar\Delta}(G_{21}^{(1)} G_{21}^{(2)*} a_1 a_2^+ + G_{21}^{(1)*} G_{21}^{(2)} a_1^+ a_2)(S_{22}^{(0)} - S_{11}^{(0)}), \quad (9)$$

where

$$\frac{1}{\hbar\Delta} = -\frac{1}{\varepsilon_2 - \varepsilon_1 - \hbar\omega_r}. \quad (10)$$

Let us write the wave function of a logical qubit in the form

$$\psi = c_1\psi_1 + c_2\psi_2, \quad (11)$$

where $\psi_1 = |0\rangle_0|1\rangle_1|0\rangle_2$ and $\psi_2 = |0\rangle_0|0\rangle_1|1\rangle_2$. Here, subscripts 0, 1 and 2 denote the states of the gate atom and the photons in resonators 1 and 2. The Schrödinger equation with the Hamiltonian (1)–(6)

$$\frac{d\psi}{dt} = -i\varepsilon_{11} c_1\psi_1 - i\varepsilon_{11} c_2\psi_2 - i\omega_r c_1\psi_1 - i\omega_r c_2\psi_2,$$

$$+ i\frac{|G_{21}^{(1)}|^2}{\hbar^2\Delta} c_1\psi_1 + i\frac{|G_{21}^{(2)}|^2}{\hbar^2\Delta} c_2\psi_2$$

$$+ i\frac{G_{21}^{(1)} G_{21}^{(2)*}}{\hbar^2\Delta} c_1\psi_2 + i\frac{G_{21}^{(1)*} G_{21}^{(2)}}{\hbar^2\Delta} c_2\psi_1, \quad (12)$$

yields a system of equations for coefficients $c_{1,2}$ of the wave function in Eqn (11):

$$\frac{dc_1}{dt} = -i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}^{(1)}|^2}{\hbar^2\Delta}\right)c_1 + i\frac{G_{21}^{(1)*} G_{21}^{(2)}}{\hbar^2\Delta} c_2, \quad (13)$$

$$\frac{dc_2}{dt} = -i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}^{(2)}|^2}{\hbar^2\Delta}\right)c_2 + i\frac{G_{21}^{(1)} G_{21}^{(2)*}}{\hbar^2\Delta} c_1. \quad (14)$$

For $G_{21}^{(1)} = G_{21}^{(2)} = G_{21}$ and the initial conditions $c_1(0) = 1$ and $c_2(0) = 0$, the solutions to Eqns (13) and (14) have the simple form

$$c_1 = \exp\left[-i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}|^2}{\hbar^2\Delta}\right)t\right]\cos\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right), \quad (15)$$

$$c_2 = i\exp\left[-i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}|^2}{\hbar^2\Delta}\right)t\right]\sin\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right), \quad (16)$$

and the wave function of the logical qubit is written as

$$\psi = \exp\left[-i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}|^2}{\hbar^2\Delta}\right)t\right]$$

$$\times\left[\cos\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)\psi_1 + i\sin\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)\psi_2\right]. \quad (17)$$

Expression (17) demonstrates high-efficiency transfer of the excitation $Q_{ET}(\varphi)$ [$\varphi = |G_{21}|^2 t/(\hbar^2\Delta)$] from resonator 1a to resonator 1b due to their indirect interaction via the gate atom, which is possible by choosing a suitable frequency mismatch. The complete transfer of excitation from one resonator to the other is possible also in the case of a resonance interaction of resonators with the gate atom ($\Delta = 0$), e.g., as shown for the scheme of a quantum transistor [24], in which the interaction of atomic ensembles via the gate atom in two crossed resonators is used.

The gate atom can be, e.g., a quantum dot that has large enough dipole moment of the optical transition [25], which is necessary for fast transfer of the single-photon excitation between ring resonators. It is important that a quantum dot can have a sufficiently large decoherence time ($\sim 10^{-4}$ s) of the ground-state spin sublevels [26, 27]. Therefore, it is possible to execute all necessary sets of operations, related to the reversible loading of the photonic qubit into the ring resonators from the memory, implementing the required quantum gates in them and the transfer of the logical photonic qubit back to the memory.

3. Logical gates

Using the above process of controlled transfer of a single-photon state between two resonators, we first describe the implementation of NOT operation using the system of photonic qubits stored in two quantum memory cells. For the operation of the single-qubit logical NOT gate, the chosen photonic logical qubit stored in two multiatom multiqubit quantum memory cells (QMa and QMb) is transferred from them via two nanowaveguide buses (5a and 5b) into one of the processor nodes consisting of two nanowaveguide ring resonators and a quantum dot. Then, ring resonators (1a and 1b) of the chosen processor node are disconnected from buses 5a and 5b of the computer and the quantum transfer of the excitation between resonators 1f and 1b mediated by the quantum dot 1c (Fig. 1) occurs in correspondence with formula (17). In this case, the initial state of the logical qubit can be written as

$$\psi_t = (\alpha|1\rangle_1|0\rangle_2 + \beta|0\rangle_1|1\rangle_2)|1\rangle_c, \quad (18)$$

where $|0\rangle_n$ and $|1\rangle_n$ are the ground and excited states of the resonator ($n = 1, 2$); $|1\rangle_c$ is the wave function of the ground state of the three-level gate atom. In the process of the excitation transfer, the wave function (18) under the action of the operator $Q_{ET}(\varphi)$ is transformed to the form

$$Q_{ET}(\varphi)\psi_i = \exp\left[-i\left(\varepsilon_{11} + \omega_r - \frac{|G_{21}|^2}{\hbar^2\Delta}\right)t\right]$$

$$\times\left\{\left\{\alpha\left[\cos\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)|1\rangle_1|0\rangle_2 + i\sin\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)|0\rangle_1|1\rangle_2\right]\right\}\right.$$

$$\left.+\beta\left[i\sin\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)|1\rangle_1|0\rangle_2 + \cos\left(\frac{|G_{21}|^2}{\hbar^2\Delta}t\right)|0\rangle_1|1\rangle_2\right]\right\}|1\rangle_c. \quad (19)$$

Note that the quantum dynamics of Eqn (19) is due to the virtual excitation of level $|2\rangle_c$ of the controlling atom that resides mainly in the ground state $|1\rangle_c$ during the evolution. For $|G_{21}|^2 t/(\hbar^2 \Delta) = \pi/2$, omitting the inessential phase factor in Eqn (19), we obtain

$$Q_{ET}\Big(\frac{\pi}{2}\Big)\psi_t = (\alpha|0\rangle_1|1\rangle_2 + \beta|1\rangle_1|0\rangle_2)|1\rangle_c, \quad (20)$$

i.e., NOT operation. For successful termination of this operation, it is necessary to stop the process of the excitation transfer between the resonators. This can be achieved either by transferring the excitation of the controlling atom from the ground state $|1\rangle_c$ to the uniting level $|b\rangle_c$, or by the adiabatically fast large detuning of the frequency of resonators from the frequency of the gate atom transition using the method [23] of the resonator frequency laser control. The qubit rotation stops because of an abrupt decrease in the atom–resonator coupling constant. After the execution of NOT operation the qubit returns to the quantum memory cells via nanowaveguide buses 5a and 5b of the computer. In a similar way one can implement the Hadamard logical gate, choosing the interaction time smaller by two times, so that

$$\frac{|G_{21}|^2}{\hbar^2 \Delta} t = \frac{\pi}{4}.$$

To implement the two-qubit logical gate of the controlled negation CNOT, one has to perform the following operations. First, from the QMb quantum memory cell, the single-photon excitation corresponding to the upper state of the controlling qubit is transferred to the ring resonator 1b of the chosen processor node. Then, this resonator is disconnected from the computer bus, and the excitation is transferred to the $|2\rangle_c$ state of the quantum dot via the $|1\rangle_c \rightarrow |2\rangle_c$ transition (Fig. 1). After that, using the external laser pulse supplied via a tapered waveguide 1w, we transfer this excitation to the blocking sublevel $|3\rangle_c$, so that the population difference in the working transition $|1\rangle_c \rightarrow |2\rangle_c$ becomes zero. Then the controlled qubit is transferred from the QMa and QMb quantum memory cells via buses 5a and 5b to ring resonators 1a and 1b, as in a single-qubit NOT gate. However, in the present case there is no excitation transfer between the ring resonators of the processor unit, since the populations of $|1\rangle_c$ and $|2\rangle_c$ states of the working transition of the quantum dot are zero.

Finally, the excitations are transferred back via the same ways into quantum memory cells: first, the excitation of the controlled qubit and then that of the controlling one is transferred. If the excitation was absent in the initial upper state of the controlling qubit in the QMb quantum memory cell, then the excitation transfer in the controlled qubit will occur as during the operation of the NOT single-qubit gate.

The described operations implement the controlled negation gate, which together with the single-qubit gates forms a universal set of gates. Therefore, an optical multiqubit quantum computer can be constructed, in which the fast execution of operations is due to using the optical control of the interaction of the single-photon resonators with a common waveguide resonator and quantum dots that provide the controllable quantum coupling between nanophotonic resonators.

The authors of [28] and [29] experimentally measured the values of the coupling constant between the quantum dot and photons in the resonator to be 100 and 160 GHz, respectively. Therefore, the execution time for the above operations can be tens of picoseconds, which allows their successful execution during a time mush less than the time of storing the information at the intermediate levels of the quantum dot. The latter can be increased in the case of electron spin states to 30 ns [30], and even to tenths [26, 27] and units [31, 32] of microseconds.

4. Conclusions

Thus, we have demonstrated theoretically the possibility of creating an optical universal quantum computer based on a quantum transistor effect using nanowaveguide resonators coupled via a controlled gate atom. Its execution speed amounts to tens of picoseconds, since the only limiting factor is the switching rate of the resonator frequency and the Rabi frequency of the quantum dot, playing the role of a gate atom. The on-line storage of quantum information in the computer is provided by the nanowaveguide quantum memory based on the photon echo, which can be used for a large number of broadband photonic qubits [19, 20, 21, 33].

In connection with the success in developing multicubit quantum memory, it is of interest to design a quantum computer, where the role of the photon echo is not only to store the photonic qubits, but also to perform logical operations. Such a version of a single-pass quantum computer was proposed in Ref. [34]. In the present paper, we describe a scheme of the optical quantum computer that has two quantum memory cells, thus allowing the implementation of a multipass nano-optical scheme of a deterministic quantum computer based on logical qubits.

It is worth mentioning the recent experimental implementation of an optical nanowaveguide resonator with Bragg gratings [35]. The linear dimensions of this nano-optical resonator can be a few centimetres, which makes it possible to couple to it many ring microresonators at once. The authors of Ref. [35] managed to place a single quantum dot at the surface of a nanowaveguide with the localisation precision ~3 μm. This localisation uncertainty is much smaller than the supposed diameter of the ring resonator, which allows successful connection of two ring resonators via a nanodot in the scheme proposed by us.

Thus, the architecture of a nano-optical quantum computer, described in the present paper, can be implemented using the already existing and intensely developed technologies based on high-Q optical resonators [22, 23, 35–38] and the principles of multiqubit quantum memory in a resonator [19, 39–42]. The multiprocessor architecture of the quantum computer will make it possible to perform parallel computations, which will accelerate task execution and facilitate the solution of the problem of decoherence suppression for the qubits present in the gate atoms and resonators or stored in quantum memory. Moreover, the use of a nanowaveguide bus will allow direct coupling of quantum processors to high-speed data transmission fibre lines. Therefore, this optical computer can find successful application in quantum communication devices, such as quantum repeaters, quantum routers and devices for quantum digital signature formation.

Acknowledgements. The work was supported by the Russian Science Foundation (Grant No. 14-12-01333).

References

1. DiCarlo L., Chow J.M., Gambetta J.M., Bishop L.S., Johnson B.R., Schuster D.I., Majer J., Blais A., Frunzio L., Girvin S.M., Schoelkopf R.J. *Nature*, **460**, 240 (2009).

2. Neeley M., Bialczak R.C., Lenander M., Lucero M.E., Mariantoni M., O'Connell A.D., Sank D., Wang H., Weides M., Wenner J., Yin Y., Yamamoto T., Cleland A.N., Martinis J.M. *Nature*, **467**, 570 (2010).
3. DiCarlo L., Reed M.D., Sun L., Johnson B.R., Chow J.M., Gambetta J.M., Frunzio L., Girvin S.M., Devoret M.H., Schoelkopf R.J. *Nature*, **467**, 574 (2010).
4. Mariantoni M., Wang H., Yamamoto T., Neeley M., Bialczak R.C., Chen Y., Lenander M., Lucero E., O'Connell A.D., Sank D., Weides M., Wenner J., Yin Y., Zhao J., Korotkov A.N., Cleland A.N., Martinis J.M. *Science*, **334**, 61 (2011).
5. Zhu X., Matsuzaki Y., Amsuss R., Kakuyanagi K., Shimo-Oka T., Mizuochi N., Nemoto K., Semba K., Munro W.J., Saito Sh. *Nat. Commun.*, **5**, 4524 (2014).
6. Andrianov S.N., Moiseev S.A. *Phys. Rev. A*, **90**, 042303 (2014).
7. Andrianov S.N., Bochkarev V.V., Moiseev S.A. *Eur. Phys. J. B*, **87**, 128 (2014).
8. Gibbs H.M. *Optical Bistability: Controlling Light with Light* (Orlando: Acad. Press, 1985).
9. O'Brien J.L., Pryde G.J., Whitep A.G., Ralph T.C., Branning D. *Nature*, **426**, 264 (2003).
10. Lanyon B.P., Barbieri M., Almeida M.P., Jennewein T., Ralph T.C., Resch K.J., Pryde G.J., O'Brien J.L., Gilchrist A., White A.G. *Nature Phys.*, **5**, 134 (2009).
11. Kok P. et al. *Rev. Mod. Phys.*, **79**, 135 (2007).
12. Knill E., Laflamme R., Milburn G.J. *Nature,* **409**, 46 (2001).
13. Munro W.J., Nemoto K., Spiller T.P. *New J. Phys.*, **7**, 137 (2005).
14. Chudzicki C., Chuang I.L., Shapiro J.H. *Phys. Rev. A*, **87**, 042325 (2013).
15. Marzlin K.-P., Wang Z.-B., Moiseev S.A., Sanders B.C. *J. Opt. Soc. Am. B*, **27**, A36 (2010).
16. Yamaguchi M., Asano T., Sato Y., Noda S. arXiv: 1101.3508 (2011).
17. O'Shea D., Junge C., Volz J., Rauschenbeutel A. *Phys. Rev. Lett.*, **111**, 193601 (2013).
18. Shomroni I., Rosenblum S., Lovsky Yu., Bechler O., Guendelman G., Dayan B. *Science*, **345**, 903 (2014).
19. Moiseev S.A., Andrianov S.N., Gubaidullin F.F. *Phys. Rev. A*, **82**, 022311 (2010).
20. Moiseev S.A., Andrianov S.N. *J. Phys. B: At., Mol. Opt. Phys.*, **45**, 124017 (2012).
21. Moiseev S.A. *Phys. Rev. A*, **88**, 012304 (2013).
22. Yariv A. *IEEE Photonics Technol. Lett.*, **14**, 483 (2002).
23. Preble S.F., Cao L., Elshaari A., Aboketaf A., Adams D. *Appl. Phys. Lett*., **101**, 171110 (2012).
24. Moiseev S.A., Andrianov S.N., Moiseev E.S. *Opt. Spektrosk*., **115**, 406 (2013) [*Opt. Spectrosc*., **115**, 356 (2013)].
25. Hennessy K., Badolato A., Winger M., Gerace D., Atature M., Gulde S., Falt S., Hu E.L., Imamoglu A. *Nature*, **445**, 896 (2007).
26. Oulton R., Greilich A., Verbin S.Yu., Cherbunin R.V., Auer T., Yakovlev D.R., Bayer M., Merkulov I.A., Stavarache V., Reuter D., Wieck A.D. *Phys. Rev. Lett*., **98**, 107401 (2007).
27. Kawaki E., Scarlino P., Ward D.R., Braakman F.R., Savage D.E., Lagally M.G., Friesen M., Coppersmith S.N., Eriksson M.A., Vandersypen L.M.K. *Nat. Nanotechnol. Lett.*, **9**, 666 (2014).
28. Fushman I., Englund D., Faraon A., Stoltz N., Petroff P., Vuckovic J. *Science*, **320**, 769 (2008).
29. Ohta R., Ota Ya., Nomura M., Kumagai N., Ishida S., Iwamoto S., Arakawa Ya. *Appl. Phys. Lett.*, **98**, 173104 (2011).
30. Langer L., Poltavtsev S.V., Yugova I.A., Salewski M., Yakovlev D.R., Karczewski G., Wojtowicz T., Akimov I.A., Bayer M. *Nat. Photonics*, **8**, 851 (2014).
31. Petta J.R., Johnson A.C., Taylor J.M., Laird E.A., Yacoby A., Lukin M.D., Marcus C.M., Hanson M.P., Gossard A.C. *Science*, **309**, 2180 (2005).
32. Greilich A., Yakovlev D.R., Shabaev A., Efros Al.L., Yugova I.A., Oulto R., Stavarache V., Reuter D., Wieck A., Bayer M. *Science*, **313**, 341 (2006).
33. Moiseev E.S., Moiseev S.A. arXiv: 1412.2459v1.
34. Manykin E.A., Mel'nichenko E.V. *Kvantovaya Elektron*., **44**, 1141 (2014) [*Quantum Electron*., **44**, 1141 (2014)].
35. Yalla R., Sadgrove M., Nayak K.P., Hakuta K. *Phys. Rev. Lett.,* **113**, 143601 (2014).
36. Barwicz T., Byun H., Gan F., Holzwarth C.W., Popovich M.A., Rakich P.T., Watts M.R., Ippen E.P., Kärtner F.X., Smith H.I. *J. Opt. Networking*, **6**, 63 (2007).
37. Watts M.R. *Opt. Lett*., **35**, 3231 (2010).
38. Bogaerts W., De Heyn P., Van Vaerenbergh T., De Vos K., Selvaraja S.K., Claes T., Dumon P., Bienstman P., Van Thourhout D., Baets R. *Laser Photonics Rev*., **6**, 47 (2012).
39. Afzelius M., Simon C. *Phys. Rev. A*, **82**, 022310 (2010).
40. Sabooni M., Kometa S.T., Thuresson A., Kröll S., Rippe L. *New J. Phys*., **15**, 035025 (2013).
41. Sabooni M., Li Q., Kröll S., Rippe L. *Phys. Rev. Lett.*, **110**, 133604 (2013).
42. Jobez P., Usmani I., Timoney N., Laplane C., Gisin N., Afzelius M. *New J. Phys*., **16**, 083005 (2014).